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Tracer tests for characterizing Malm geothermal reservoirs within the German BMWi project TRENDS: a feasibility study

Dina S. Dewi, Augustine O. Enomayo, Julia Ghergut *,
Shyamal Karmakar, Martin Sauter, Bianca Wagner

University of Göttingen, Geoscience Centre (GZG), Applied Geology Dept., Goldschmidtstr. 3, 37077 Göttingen, Germany

Abstract

The research project TRENDS (“Tracer-assisted evaluation of reservoir behavior under expansive deployment schemes for Malm geothermal resources in the Munich area”) aims at quantifying the hydrogeology of Malm geothermal resources with a focus on fluid transport parameters, and identifying possible restrictions to reservoir exploitation resulting from either hydraulic or geothermal heat supply ‘competition’ effects between ‘adjacent’ reservoirs. While it is beyond doubt that these aims cannot be achieved without the use of some fluid-based tracking procedure for quantifying fluid transport (viz.: tracer tests), the use of artificial tracers is challenged by the very large size of Malm geothermal reservoirs, implying very long residence times (RT) of circulating fluids and strong dilution of tracers therein. A series of M. Sc. thesis projects conducted at the University of Göttingen addresses tracer test design, evaluation and interpretation problems specifically associated with the ‘very long RT’ issue. Preliminary findings from these projects, and some recommendations for future tracer test design are presented.

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Keywords: tracer test; inter-well; single-well; residence time; flow-storage repartition; Lorenz plot; reef facies; bedded facies; geothermal; Malm; Molasse basin; Munich; Sauerlach

* Corresponding author. Tel.: +49-551-39-33156 ; fax: +49-551-39-9379.
E-mail address: iulia.ghergut@geo.uni-goettingen.de

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1. Motivation, and aims of this study

The research project TRENDS ("**T**racer-assisted evaluation of **r**eservoir b**e**havior under expa**n**sive **d**eployment **s**chemes for Malm geothermal resources in the Munich region"), initiated with the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU), and implemented by the German Federal Ministry for Economic Affairs and Energy (BMWi), aims at [1]

- investigating the hydrogeology of Malm geothermal resources with a focus on fluid transport parameters (transport effective porosity, dual-porosity features, fluid-rock interface area density) and on facies-specific void-space structure characterization at various scales, and quantifying the relevant facies distribution at reservoir scale,
- quantifying fluid flow and predicting heat transport therein under various scenarios for the future deployment and exploitation of Malm geothermal resources in the SE-German area of the Molasse basin,
- identifying possible restrictions to reservoir exploitation resulting from either hydraulic or geothermal heat supply 'competition' effects between 'neighboring' reservoirs (whereby 'neighboring' does not necessarily mean 'spatially-adjacent' but may also refer to hydraulic and/or fluid transport connectivity by virtue of large-scale fault zones).

While it is beyond doubt that these goals cannot be achieved without the use of some fluid-based tracking procedure for quantifying fluid transport, viz. tracer tests [1,2], the use of artificial tracers is challenged [3] by the very large size of Malm geothermal reservoirs, implying very long residence times (RT) of circulating fluids and strong dilution of tracers therein, thereby requiring (i) very long duration of signal observation (fluid sampling) to get 'sufficient' information from tracer signals, (ii) very large quantities of tracers (tens to hundreds kg for tracer species detectable in the several-ppb range) to be added as circulation spikes at geothermal injection wells, in order to ensure measurable signals at geothermal production wells.

On the other hand, the successful implementation of various options (well doublets or triplets, with or without stimulation treatments) for geothermal reservoir development in Malm aquifers of the Munich region [4,5] is increasingly attracting the interest of students visiting the International M. Sc. Course "Hydrogeology and Environmental Geoscience" (HEG) at the University of Göttingen. Currently, a number of M. Sc. thesis projects address tracer test design, evaluation and interpretation problems specifically associated with the 'very long RT' issue: Ms. Dina Silvia Dewi [6] investigates the effects of premature interruption of tracer signal observation on the shape of flow-storage diagrams derived from (more or less 'incomplete') tracer signals; Mr. Augustine Osaigbovo Enomayo [7] uses semi-analytical model approximations to simulate tracer signals from single-well and inter-well tests intended to characterize Malm geothermal reservoirs with a focus on reef/bedded facies distribution, and derives some recommendations for tracer test design; Mr. Zubair Munir [8] evaluates the effects of facies-dependent dispersion and permeability contrasts on inter-well tracer signals predicted for the geothermal well triplet at the Sauerlach site in a deep Malm aquifer in the Munich region; Mr. Ahrar Haider Naqvi [9] addresses the use of flow-storage diagrams for characterizing subsurface flow systems with very large immobile-fluid compartments from a more general (not site-specific) viewpoint; Mr. Benjamin Olukunle Ekeade [10] uses Lorenz diagrams to re-evaluate the available data and competing models for a series of tracer tests conducted at the Olkaria geothermal site in Kenya, and derives generic tracer-methodological recommendations for projects dealing with fractured-porous reservoir systems; Mr. Rizwan Mohsin [11] examines competing approaches to tracer signal inversion for the Soultz-sous-Forêts site in the Upper Rhine Graben, discusses some analogies to faulted-fractured-fissured-porous reservoirs in the Malm-Molasse basin and derives some recommendations for future tracer test evaluation therein; last not least, Mr. Nawfal Ahmed Saleh Khaleefah and Ms. Swathi Mohandas Surekha [12] investigate the applicability of 'thermal tracer' (including thermal tomography) techniques for reservoir characterization, depending on hydrogeologic heterogeneity (fracture-dominated, fractured-porous, multiple-porosity, with moderate or weak permeability contrasts in layered, slanted, lenticular, etc) patterns.

A major endeavor common to all of these projects is to finally tell (i) what knowledge gain can be derived from single- and/or inter-well tracer tests in (very) large-sized reservoirs whose fractured / fissured / karstified / porous character is variably expressed in the (limited number of) available deep boreholes, (ii) what are the (cumulated?) reasons for ambiguity in hydrogeologic parameter inversion from measured tracer signals (reasons related to test design? to the limited duration of fluid sampling? to the in-situ behavior of tracers and their more or less predictable interaction with reservoir rocks and fluids? or to intrinsic properties of the reservoir, structural and/or hydrogeologic?), and (iii) what elements of this knowledge can be transferred to the evaluation of fractured-fissured-porous reservoirs in world regions with different geotectonic/geological settings and different karstification history.

Nomenclature

F, *S*	flow capacity, storage capacity (normalized, dimensionless)
FSR	flow-storage repartition
(M)RT	(mean) residence time, with RTD for residence time distribution
Pe	Peclet number (dimensionless)
T	reef-to-total transmissivity ratio (dimensionless)
k	reef-to-bedded permeability ratio (dimensionless)
p	reef-to-bedded porosity ratio (dimensionless)
y	reef-to-bedded thickness ratio (dimensionless)

2. On the use of flow-storage repartition (FSR) analysis for reservoir characterization

In [1] and [2], it had been recommended to use FSR (as originally introduced by [13] for characterizing what M. Shook deemed as "geothermal reservoir geometry"); however, [1] also warned that FSR gained from prematurely-interrupted tracer signal observations tend to systematically under-estimate the storage fraction hosting a given flow contribution (or over-estimate the flow contribution hosted by given storage fraction) in mono-dispersive flow systems, whereas this trend can be reverted in more complex flow systems involving the superposition of divergent, high-rate flow field along large-area planar structures (major fractures or fault zones), and slow matrix-fracture exchange fluxes [14].

FSR analysis [13] is a versatile tool for characterizing subsurface flow and transport systems. FSR can be derived from tracer signals measured in inter-well tests, if certain requirements [1,2] are met – basically, the same as required for equivalence between fluid residence time distribution (RTD) and measured inter-well tracer signal (pre-processed and de-convolved if necessary, as described in [13]). In a more general approach [2], a FSR is derived from a RTD as a trajectory in normalized {1st, 0th}-order statistical moment space; more intuitively, as a parametric plot of 0th-order against 1st-order statistical moments of RTD truncated at time *t*, with *t* as a parameter running from the first tracer input to the latest available tracer sampling; 0th-order moments being normalized by the total tracer recovery, and 1st-order moments by the mean RT. Fracture-dominated systems plot in the upper left (high *F*, low *S*) region of FSR diagrams; 'plug' flow in a homogeneous, dispersion-less mono-continuum (Peclet number Pe = ∞) displays as a straight line from $\{F,S\}=\{0,0\}$ to $\{F,S\}=\{1,1\}$. This analysis tool appears particularly attractive [1] for characterizing markedly heterogeneous, porous-fissured-fractured (partly karstified) formations like those targeted by geothermal exploration in the Malm-Molasse basin in Southern Germany, and especially for quantifying flow and transport contributions from contrasting facies types ('reef' versus 'bedded' and 'transitional' facies, terminology and underlying knowledge being explained in detail by [15,16,17]). However, tracer tests conducted in such systems with inter-well distances of some hundreds of metres (as required by economic considerations on geothermal reservoir sizing) face the issue [3] of very long residence times – and thus the need to deal with incomplete (truncated) signals. For the geothermal well triplet at the Sauerlach site [4] in the Munich region, tracer MRT exceeding 2 years have been predicted by [1], and signal tails decreasing by less than 50% over longer than 10 years, which puts great uncertainty on the (extrapolation-based) normalizing factors needed to calculate FSR, and on FSR extrapolation itself [1,2,3]. Looking at the Sauerlach example (Fig. 1), we find that premature interruption of tracer sampling systematically leads to overestimating the reservoir's storage capacity and underestimating its flow capacity, with misestimation generally increasing as the bedded/reef interfacial area per volume is increased.

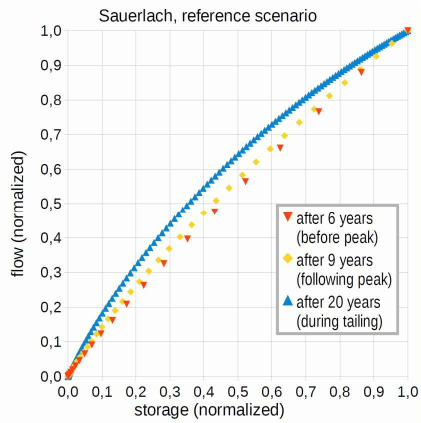

Fig. 1. Flow-storage repartition shift with increasing duration of tracer signal observation.

3. Inter-well and single-well tracer tests for Malm reservoir characterization

The aims of this section are to (i) evaluate the ability of artificial-tracer tests to measure geothermally-relevant parameters of a typical Malm reservoir (represented by a generic model), especially parameters associated with fluid transport (aquifer porosity and thickness), and possibly with reservoir heterogeneity (ratio between 'reef' and 'bedded' facies compartments as described by [15,16,17]), and (ii) compare between the performance of inter-well and single-well tracer tests, in terms of parameter sensitivity and possible ambiguity impeding parameter inversion.

3.1. Generic conceptual model for tracer test analysis

As a quintessence from decade-long work conducted by prominent German hydrogeologists on Malm aquifers of the Southern Franconian Alb [16,17] and, later on, of the Munich region [4,5,15], one can derive three generic conceptual models, reflecting the hydro-stratigraphical profiles typically encountered in deep boreholes drilled across the entire Malm formation thickness (~600 m for the Munich region), with varying contributions from the so-called 'reef' facies (German: *Massenfazies*) supposed to provide for 'aquifer' behavior (high fluid mobility), and from the so-called 'bedded' facies (German: *Platten-/Bankkalkfazies*) supposed to act as stagnant-fluid (low fluid mobility) compartments. More specifically, for the purposes of the present study, one can assume the reservoir is comprised of 'reef' and 'bedded' facies compartments of spatially varying thickness and also (to a lesser extent) varying porosity and permeability. Since inter-well tracer tests reflect some sort of flowpath-averaged values of these parameters, whereas single-well tracer tests (only capturing a relatively small radial distance around the well) reflect the local values of those hydrogeologic parameters, for the generic model of this section we shall assume a layered reservoir structure that is reducible to just two gross compartments: (i) the juxtaposition of all 'reef' components, of total thickness $B_{[\mathrm{reef}]}$, average (local) porosity $n_{[\mathrm{reef}]}$, average (local) permeability $K_{[\mathrm{reef}]}$, and average (local) dispersivity expressed by Peclet number $\mathrm{Pe}_{[\mathrm{reef}]}$, alongside with (ii) the juxtaposition of all 'bedded' components, of total thickness $B_{[\mathrm{bedded}]}$, average (local) porosity $n_{[\mathrm{bedded}]}$, average (local) permeability $K_{[\mathrm{bedded}]}$, and average (local) dispersivity expressed by $\mathrm{Pe}_{[\mathrm{bedded}]}$, irrespective of their fluid transport process connectivity. Regarding the meaning of Peclet numbers, a more detailed discussion will follow in section 3.2.; we also introduce dimensionless notation for reef-to-bedded ratios of: permeability $k = K_{[\mathrm{reef}]} / K_{[\mathrm{bedded}]}$, thickness $y = B_{[\mathrm{reef}]} / B_{[\mathrm{bedded}]}$, porosity $p = n_{[\mathrm{reef}]} / n_{[\mathrm{bedded}]}$; as well as reef-to-total and bedded-to-total transmissivity ratios: $T = ky / (ky{+}1)$, and $(1 - T) = 1 / (ky{+}1)$.

For tracer signal predictions (inter-well and single-well), we assume the model described by [18] for homogeneous aquifer formations can be extended to the case of layered reservoirs, by way of superposition, as described by [19] who applied transmissivity-weighted averaging to the formulae provided by [18]. Strictly speaking, this semi-analytical model approach is valid only under steady-state flow conditions, and in the low-dispersivity limit (Pe >> 1). Quasi steady-state hydraulics can be ensured for inter-well tests and for the 'push' stages of single-well tests (by the timing of tracer additions, such as to allow for quasi steady-state pressure buildup before adding tracers), but might be violated during early 'pull' stages of single-well tests (where the 'timing' of tracer backflow can no longer be steered by way of experiment design); however, since hydraulic diffusivity values for Malm formations are rather high, ensuring fast drawdown [4], the overall errors introduced by hydraulic unsteadiness will remain low. Since we deal with only two gross components, total 'reef' and total 'bedded', the integrals (1) and (2) written by [19] reduce to only two terms each, weighted by T and $(1 – T)$, respectively.

3.2. Parameter sensitivity findings

Parameter sensitivity findings for inter-well tests are illustrated by Figs. 2 – 4, whereas Fig. 5 shall show particular findings for single-well tests, based on the generic model of section 3.1 alongside with some more specific considerations on near-well dispersion (such considerations not being required for the inter-well case). Figure 2 shows the influence of heterogeneity or (macro-)dispersive processes on simulated tracer breakthrough at the geothermal production well, during inter-well circulation; the upper section assumes – rather unrealistically – a stronger dispersion in the bedded, than in the reef facies ($Pe_{[bedded]}$=10, $Pe_{[reef]}$=100), whereas the lower section assumes – more realistically – stronger dispersion in the reef, than in the bedded facies ($Pe_{[reef]}$=10, $Pe_{[bedded]}$=100); else, both sections assume the same set of values for reef/bedded formation thickness, permeability and porosity ratios (y=2; k=2; p=½ , …, 16 as indicated by colors). Figure 3 shows the influence of reef-vs.-bedded porosity contrast on simulated tracer breakthrough at the geothermal production well, during inter-well circulation, expressed by 6 values (colors) of reef/bedded porosity ratio p = ½, 1, 2, 4, 8, 16, assuming a moderate (k=4, upper section), or a strong permeability contrast (k=32, lower section); else, all scenarios assume the same reef/bedded formation thickness ratio (y=2), as well as invariant dispersion within each facies type ($Pe_{[reef]}$=20, $Pe_{[bedded]}$=40). Figure 4 shows the influence of reef-vs.-bedded permeability contrast on simulated tracer breakthrough signals at the geothermal production well, during inter-well circulation, expressed by 6 values (colors) of reef/bedded permeability ratio k = 1, 2, 4, 8, 16, 32; else, all scenarios assume the same reef/bedded formation thickness and porosity ratios (y=2; p=4), as well as invariant dispersion within each facies type ($Pe_{[reef]}$=20, $Pe_{[bedded]}$=40).

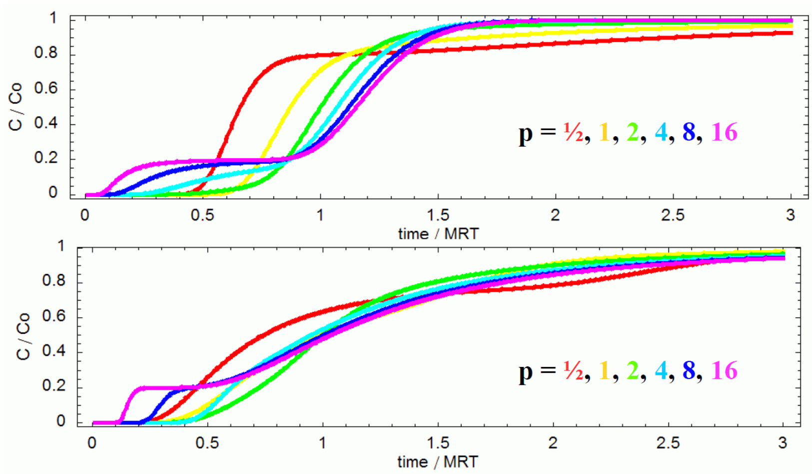

Fig. 2. Influence of dispersion on tracer breakthrough in inter-well tests.

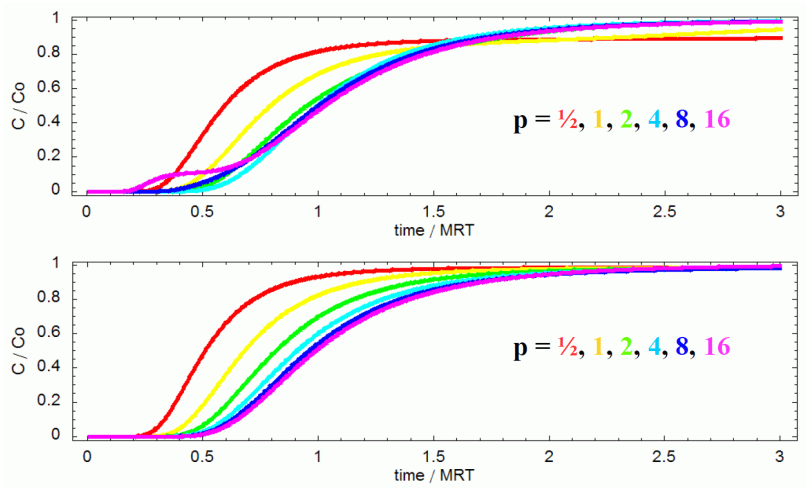

Fig. 3. Influence of reef-vs.-bedded porosity contrast on tracer breakthrough in inter-well tests.

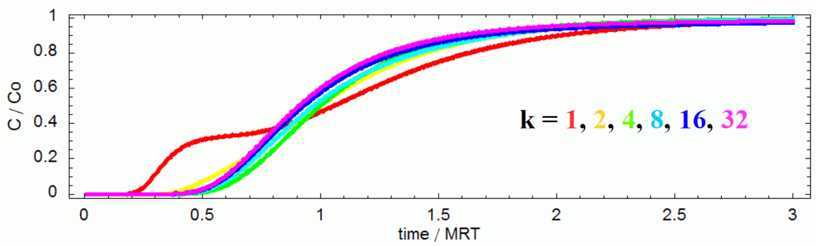

Fig. 4. Influence of reef-vs.-bedded permeability contrast on tracer breakthrough in inter-well tests.

For single-well tests, the model approach introduced in section 3.1 needs some further analysis regarding the treatment of dispersion processes, comprising hydrodynamic dispersion (which occurs even in uniform advective flow in a homogeneous mono-porous continuum), alongside with the effects of near-well flow-medium and/or flow-field heterogeneity, possibly including length scale effects. If dispersivity can be assumed as a scale-invariant length value for each facies type, then single-well tracer 'pull' signals will depend on factors k and y separately as well as on a characteristic 'test design length' given by Sqrt($V_{inj,tot}$ / π B_{tot}), with $V_{inj,tot}$ denoting the total volume of spiked fluid injected during the 'push' stage, and B_{tot} the total formation thickness addressed by the single-well test (by either open-hole or well-screen intervals). If dispersivity for each facies type can be regarded as a scale-proportional quantity, then Pe becomes scale-invariant, and single-well tracer 'pull' signals will depend only on $Pe_{[reef]}$ and $Pe_{[bedded]}$, which now denote the scale-invariant Peclet numbers characterizing the two facies types at near-well scale. Figure 5 illustrates how tracer signals from single-well push-pull tests, assuming scale-invariant Pe at near-well scale, depend on the product $k{\cdot}y$, i. e. on the transmissivity ratio between the cumulated reef and bedded facies intervals encountered at the particular borehole chosen to conduct a single-well test. It appears that when scale-proportional dispersivity values are assumed, concentration signals depend only on the product $k{\cdot}y$, whereas k and y cannot be determined independently from each other only by using tracer signals from a single-well push-pull test. When fixed (scale-independent) dispersivity values are assumed, then it is possible in principle to determine both k and y by using at least two differently-sorbing tracers, but the procedure shall be more intricate, and requires a priori knowledge of tracer sorptivity for the two rock facies types.

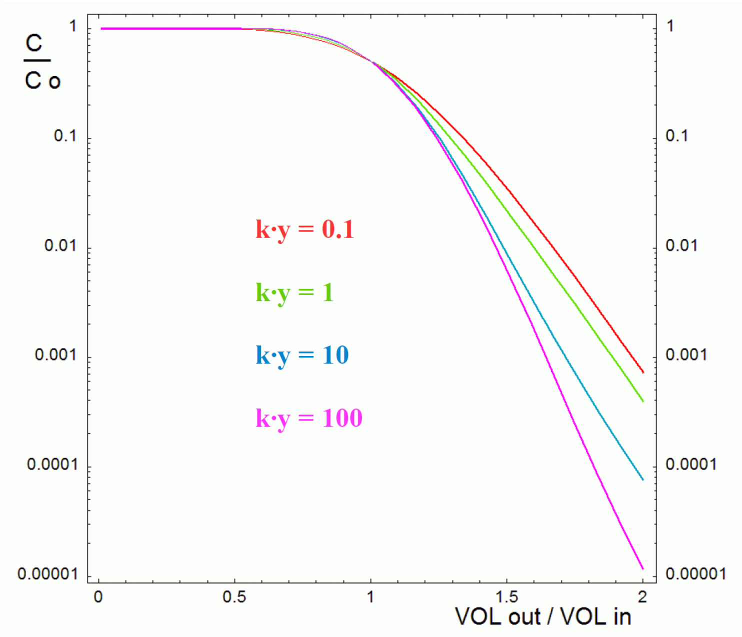

Fig. 5. Simulated tracer signals for single-well push-pull tests, assuming scale-proportional dispersivity at near-well scale.

4. Recommendations for tracer test design

Summarizing, from Figures 2 – 5 it can be seen that:

(1a) inter-well tracer test signals are most sensitive to aquifer porosity values as well as to facies transmissivity ratios, as long as reef-versus-bedded facies contrasts remain moderate; when the transmissivity contrast, or the total void-space volume contrast between the two facies compartments is extremely high, the stagnant-fluid compartments 'feel' like nonexistent in the mono-dispersive continuum approach; (1b) inter-well tracer test signals are also sensitive to dispersion processes, especially their shape at early stages of production sampling;

(2a) the dimensioning of tracer slugs to inject in inter-well tests should be such that, for a continuous tracer addition, $0.01\times C_0$ exceeds not only the detection limit (DL), but also the quantification limit (QL) value for the respective tracer species; in case of a short-pulse ('Dirac') tracer injection of total quantity M_1, the notation C_0 becomes meaningless and should be replaced by the ratio M_1/V_1, where V_1 is an estimation of the total void-space volume in the reservoir; (2b) the dimensioning of tracer slugs to inject in single-well tests should be such that $0.00001\times C_0$ exceeds not only the DL, but also the QL value for the respective tracer species (to be recalled, QL is typically 10× to 20× higher than DL);

(3) the disambiguation of a single-well test's tracer signal inversion in terms of aquifer thickness and/or porosity necessitates a pre-defined dispersivity model (a sort of 'constitutive relationship' between dispersivity and porosity, or between dispersivity and the effective flow cross section); this is a task for future research, combining results from laboratory measurements on rock core samples and from field-scale tests;

(4) if the selection of tracer species available in sufficient quantity (in accordance with 2a) is rather scarce, then inter-well tests should be given priority against single-well tests, despite the fact that single-well tests are considerably cheaper and faster to conduct, than inter-well tests (which require long-term sampling);

(5) research into sorptive tracers for carbonatic rock is worthwhile pursuing; currently, most tracer species available for practical applications are known to be non-sorptive or exhibit very little sorption on carbonatic rock at prevailing in-situ pH values; if moderately-sorptive tracers would become available, they would significantly reduce the ambiguity of parameter inversion from single-well tracer push-pull tests.

Last not least, recalling Figure 1, it would be interesting to correlate FSR findings with the tracer-based approach to facies identification for the shallower Malm aquifers of the Southern Franconian Alb, proposed by [16,17], as well as with expectations from the direct (i. e., distributed-parameter) modeling of matrix-diffusive effects [20] on measured tracer signals.

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